

穿透非均质储层的复杂轨迹井产量计算新方法

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摘要:解析法和半解析法计算水平井产量的公式一般要求油藏储层均质,且井轨迹平行于油藏边界,难以准确地计算复杂轨迹井的产量。根据井轨迹和储层渗透率把油藏划分为若干区域,不同区域渗透率取值不同,且井轨迹可不平行边界。通过引入点源函数法,基于定压油藏边界建立了非均质性储层复杂轨迹井的产量分段积分相似解,利用 Ouyang 模型计算了井筒内流动的沿程压力损失。该方法避免了数值模拟中数值弥散的发生,只需输入较少的参数就可以对复杂轨迹井进行快速产能评价。实例计算结果表明:①复杂轨迹井井筒内的流量从指端到跟端逐渐增大;②由于储层的非均质性,各段流量分布并不均匀,渗透率高的部位流量也高;③井筒压降从指端到跟端同样逐渐增大,由于流量分布不均匀,因此不同轨迹段在井筒内压降也不相等。该方法计算结果与 Eclipse 数模方法一致,表明该方法是可行的。应用该方法计算的油井产量与油田现场生产对比,预测油井产量相对误差小于 5%,能满足现场油藏工程研究的需要。

关键词:非均质储层;点源函数;复杂轨迹井;产量计算

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A new method for production calculation of complex trajectory wells in heterogeneous reservoir

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Abstract: Analytical and semi-analytical formulas for production calculation of horizontal wells generally require the reservoirs being homogeneous and well trajectory parallel reservoir boundary, which make them unsuitable for complex trajectory wells. In this paper, the reservoir is divided into several regions based on well trajectory and permeability. Each region has different permeability, and the well trajectory within the region may be unparallel with the boundary. The point source function method is introduced to establish the segmented integral similarity solution for the production of complex-trajectory well in heterogeneous and constant-pressure-boundary reservoir, and the Ouyang model is used to calculate the pressure loss along the wellbore. This method can avoid numerical dispersion in simulation, and provide a fast production evaluation with fewer input parameters. Case study result shows that flow rate in wellbore with complex trajectory increases from toe to heel, the reservoir inflow rate is different in each segment due to reservoir heterogeneity and is high in the high permeability reservoir region, the pressure drop within the wellbore also increases from toe to heel and is different in each wellbore segment due to the uneven distribution of flow rate. The result of this method is consistent with that of Eclipse, confirming its feasibility. In comparison with the metered oil production in field, the calculated production of complex trajectory well has an error of less than 5%, showing that it can satisfy the demand of real-field reservoir engineering research.

Key words: heterogeneous reservoir, point-source function, complex-trajectory well, production calculation

近十年来,复杂轨迹井开发技术在油气田开发领域取得突飞猛进的发展,已经由单一的水平段发展为最大限度接触油藏面积的复杂轨迹井段(又称复杂结构井技术)。该技术不仅在常规油气藏开发的剩余油挖潜应用广泛,而且已成为包括页岩油气、致密油气、深水油田等非常规油气藏开发不可或缺的主导技术之一^[1-3]。现场实践表明,复杂轨迹井技术不仅能提高

单井产量,而且能提高油田的采收率,使很多无法开发的油田获得经济有效地开发。复杂轨迹井与油藏接触面积大,克服油藏储层非均质性对油井产量的制约,实现单井经济效益最大化^[4]。

目前,水平井已具有较为配套的单井产量计算公式包括计算定压边界油藏的稳态法和计算封闭边界油藏的拟稳态法。对于定压边界油藏水平井产量的经典

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公式主要包括 Joshi 模型^[5]、Bulter 模型^[6]、范子菲模型^[7]和 Furui 模型^[8]。Joshi 模型要求水平段长度相对于油藏边界长度小,即低穿透比能满足压力等势线呈椭圆形。其余几个模型要求水平段的穿透比为 1,即满足垂直于水平段的流线相互平行地流入井筒。国内很多学者在这些模型基础上进一步推导了一些改进公式^[9-12],这些公式的多假设油藏呈箱型、均质,且水平段与某一边界平行。

复杂轨迹井与传统水平井有很大的差异,主要体现在长井眼段与油藏接触,穿透多段非均质性储层,且在油藏内的井身轨迹复杂多变,此类井的产量计算未能得到较为满意地解决。国内很多学者也开展了很多探索,主要集中在结构简单水平井的井筒摩阻计算、多分支井间干扰、射孔方式对产量的影响等方面,但大多考虑单一因素对产量的影响^[13-14]。考虑多因素对计算复杂轨迹井产量的方法在文献中比较少见。

1 复杂轨迹井流动模型建立

假定油藏形状为箱型,油藏上、下边界封闭,其余 4 个外边界定压(图 1)。复杂结构井井眼轨迹在油藏内可以为任意曲线形状,沿程流动阻力不断发生变化。为精确地描述油藏流入井筒的渗流和井筒内的流体管流分布,依据油藏非均质性和井眼轨迹,将复杂轨迹井的井筒分段计算,使得每一微段井筒近似为直线并且考虑微井段对应储层的非均质性。

假定连续的井眼曲线轨迹可离散为 N 个微井段,第 1 个微段为复杂轨迹井的指端,而第 N 个微段为复杂轨迹井的跟端(图 2)。每个微井段都能穿越对应油藏的非均质储层段,微井段的节点压力受井筒内沿程摩阻分布的影响,假设第 i 个井筒微段所在储层 x, y, z 方向渗透率分别为 $K_{x,i}, K_{y,i}, K_{z,i}$,微段长度为 L_i ,应井筒内流量为 q_i ,井筒压力为 p_i 。

每一微井段相当于一个独立的线汇,由一系列点汇连接而成。点汇位于井筒横截面圆心位置,并且过

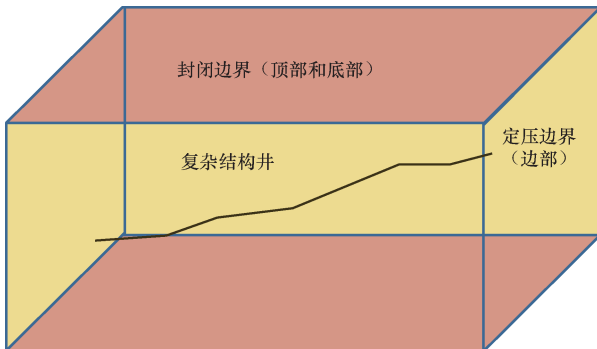


图1 油藏与井筒物理模型示意图

Fig. 1 Reservoir and wellbore trajectory model

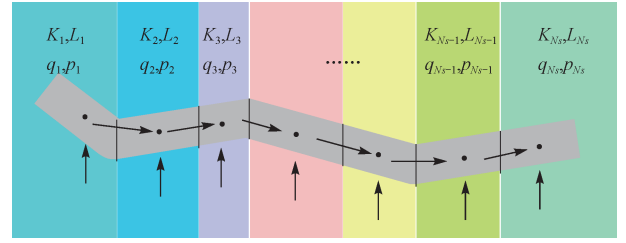


图2 非均质储层内复杂轨迹井的管流模型

Fig. 2 Pipe flow model of complex trajectory well in heterogeneous reservoirs

点汇的井筒横截面上压力均相等。因而点汇处的压力代表了和油藏接触的井筒外边界的油藏压力。在进行空间上的压力叠加时,考虑各微井段间相互干扰,则 i 个微井段的压力降为:

$$p_R - p_i = \sum_{j=1}^N \left\{ \frac{1.842 \times 10^{-3} B q_j}{a b h L_j \Phi C_i} \int_0^t \oint_{l_j} G[(x_i, y_i, z_i), l_j, \tau] dl_j d\tau \right\} \quad (1)$$

式中: p_R 为油藏初始压力, MPa; p_i 为第 i 个微井段中心点压力, MPa; B 为原油体积系数, m^3/m^3 ; q_j 为第 j 个微井段的流量, m^3/d ; a, b, h 分别为模拟油藏的长、宽、高, m; L_j 为第 j 个微井段的长度, m; Φ 为孔隙度, %; C_i 为综合压缩系数, MPa^{-1} ; x_i, y_i, z_i 为第 i 个微井段的中点坐标; l_j 为第 j 个微井段轨迹; t 为生产时间, d; τ 为时间积分变量。

公式(1)中 $G[(x_i, y_i, z_i), l_j, \tau]$ 为 Green 函数, 根据 Neumann 积原理可以表示为^[15-16]:

$$G[(x_i, y_i, z_i), l_j, \tau] = S_x(x_i, x_j, \tau) \cdot S_y(y_i, y_j, \tau) \cdot S_z(z_i, z_j, \tau) \quad (2)$$

$$S_x(x_i, x_j, \tau) = 2 \sum_{n=1}^{\infty} \left[\sin \frac{n\pi x_i}{a} \sin \frac{n\pi x_j}{a} \exp \left(-\frac{n^2 \pi^2 \eta_{x,j} t}{a^2} \right) \right] \quad (3)$$

$$S_y(y_i, y_j, \tau) = 2 \sum_{m=1}^{\infty} \left[\sin \frac{m\pi y_i}{b} \sin \frac{m\pi y_j}{b} \exp \left(-\frac{m^2 \pi^2 \eta_{y,j} t}{b^2} \right) \right] \quad (4)$$

$$S_z(z_i, z_j, \tau) = 1 + 2 \sum_{k=1}^{\infty} \left[\cos \frac{k\pi z_i}{h} \cos \frac{k\pi z_j}{h} \exp \left(-\frac{k^2 \pi^2 \eta_{z,j} t}{h^2} \right) \right] \quad (5)$$

式中: S_x, S_y, S_z 表示点 (x_i, y_i, z_i) 处的瞬间点变换函数; n, m 和 k 为正整数变量; $\eta_{x,j} = \frac{K_{x,j}}{\Phi_j \mu C_i}$, $\eta_{y,j} = \frac{K_{y,j}}{\Phi_j \mu C_i}$, $\eta_{z,j} = \frac{K_{z,j}}{\Phi_j \mu C_i}$; $K_{x,j}, K_{y,j}, K_{z,j}$ 分别为第 j 个井段在 x, y, z 方向的渗透率, $10^{-3} \mu\text{m}^2$; μ 为流体粘度, $\text{MPa} \cdot \text{s}$ 。

以 y 方向为例,介绍 Green 函数的简化过程。把 Green 函数代入公式(1),可得:

$$\begin{aligned}
\Delta p_i &= p_0 - p_i(x_i, y_i, z_i, t) \\
&= \sum_{j=1}^N \left\{ \frac{1.842 \times 10^{-3} B q_j}{ab h L_j \Phi C_i} \left[\frac{4b}{\pi^3} \sum_{n=1}^{\infty} \sum_{m=1}^{\infty} \left(\frac{\sin \frac{n\pi x_i}{a} \sin \frac{n\pi x_j}{a} \sin \frac{m\pi y_i}{b} \left(\cos \frac{m\pi y_{j,1}}{b} - \cos \frac{m\pi y_{j,2}}{b} \right)}{m \left(\frac{n^2 \eta_{x,j}}{a^2} + \frac{m^2 \eta_{y,j}}{b^2} \right)} \right. \right. \right. \\
&\quad \left. \left. \left(1 - \exp \left(- \left(\frac{n^2 \eta_{x,j}}{a^2} + \frac{m^2 \eta_{y,j}}{b^2} \right) \pi^2 t \right) \right) \right) + \right. \\
&\quad \left. \frac{8b}{\pi^3} \sum_{n=1}^{\infty} \sum_{m=1}^{\infty} \sum_{k=1}^{\infty} \left(\frac{\sin \frac{n\pi x_i}{a} \sin \frac{n\pi x_0}{a} \sin \frac{m\pi y_i}{b} \left(\cos \frac{m\pi y_{j,1}}{b} - \cos \frac{m\pi y_{j,2}}{b} \right) \cos \frac{k\pi z_i}{h} \cos \frac{k\pi z_j}{h}}{m \left(\frac{n^2 \eta_{x,j}}{a^2} + \frac{m^2 \eta_{y,j}}{b^2} + \frac{k^2 \eta_{z,j}}{h^2} \right)} \right. \right. \\
&\quad \left. \left. \left(1 - \exp \left(- \left(\frac{n^2 \eta_{x,j}}{a^2} + \frac{m^2 \eta_{y,j}}{b^2} + \frac{k^2 \eta_{z,j}}{h^2} \right) \pi^2 t \right) \right) \right) \right] \right\} \quad (6)
\end{aligned}$$

对于拟稳态状态下的流动,令 $t \rightarrow \infty$, 可得:

$$\begin{aligned}
\Delta \bar{p} &= \bar{p}_R - p(x_i, y_i, z_i) \\
&= \sum_{j=1}^N \left\{ \frac{1.842 \times 10^{-3} B q_j}{ab h L_j \Phi C_i} \left[\frac{4b}{\pi^3} \sum_{n=1}^{\infty} \sum_{m=1}^{\infty} \frac{\sin \frac{n\pi x_i}{a} \sin \frac{n\pi x_j}{a} \sin \frac{m\pi y_i}{b} \left(\cos \frac{m\pi y_{j,1}}{b} - \cos \frac{m\pi y_{j,2}}{b} \right)}{m \left(\frac{n^2 \eta_{x,j}}{a^2} + \frac{m^2 \eta_{y,j}}{b^2} \right)} + \right. \\
&\quad \left. \frac{8b}{\pi^3} \sum_{n=1}^{\infty} \sum_{m=1}^{\infty} \sum_{k=1}^{\infty} \frac{\sin \frac{n\pi x_i}{a} \sin \frac{n\pi x_j}{a} \sin \frac{m\pi y_i}{b} \left(\cos \frac{m\pi y_{j,1}}{b} - \cos \frac{m\pi y_{j,2}}{b} \right) \cos \frac{k\pi z_i}{h} \cos \frac{k\pi z_j}{h}}{m \left(\frac{n^2 \eta_{x,j}}{a^2} + \frac{m^2 \eta_{y,j}}{b^2} + \frac{k^2 \eta_{z,j}}{h^2} \right)} \right] \right\} \quad (7)
\end{aligned}$$

方便起见,令 A_{ij} 为第 j 个微井段对第 i 个微井段中心点的影响因子:

$$\begin{aligned}
A_{ij} &= \frac{1.842 \times 10^{-3} B q_j}{ab h L_j \Phi C_i} \left[\frac{4b}{\pi^3} \sum_{n=1}^{\infty} \sum_{m=1}^{\infty} \frac{\sin \frac{n\pi x_i}{a} \sin \frac{n\pi x_j}{a} \sin \frac{m\pi y_i}{b} \left(\cos \frac{m\pi y_{j,1}}{b} - \cos \frac{m\pi y_{j,2}}{b} \right)}{m \left(\frac{n^2 \eta_{x,j}}{a^2} + \frac{m^2 \eta_{y,j}}{b^2} \right)} + \right. \\
&\quad \left. \frac{8b}{\pi^3} \sum_{n=1}^{\infty} \sum_{m=1}^{\infty} \sum_{k=1}^{\infty} \frac{\sin \frac{n\pi x_i}{a} \sin \frac{n\pi x_j}{a} \sin \frac{m\pi y_i}{b} \left(\cos \frac{m\pi y_{j,1}}{b} - \cos \frac{m\pi y_{j,2}}{b} \right) \cos \frac{k\pi z_i}{h} \cos \frac{k\pi z_j}{h}}{m \left(\frac{n^2 \eta_{x,j}}{a^2} + \frac{m^2 \eta_{y,j}}{b^2} + \frac{k^2 \eta_{z,j}}{h^2} \right)} \right] \quad (8)
\end{aligned}$$

则公式(7)可表达为:

$$p_0 - p_i = \sum_{j=1}^N A_{ij} q_j \quad (9)$$

公式(9)矩阵表达式为:

$$\begin{bmatrix} A_{11} & A_{12} & A_{13} & \cdots & A_{1N} \\ A_{21} & A_{22} & A_{23} & \cdots & A_{2N} \\ A_{31} & A_{32} & A_{33} & \cdots & A_{3N} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ A_{N1} & A_{N2} & A_{N3} & \cdots & A_{NN} \end{bmatrix} \begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ \vdots \\ q_N \end{bmatrix} = \begin{bmatrix} p_0 - p_1 \\ p_0 - p_2 \\ p_0 - p_3 \\ \vdots \\ p_0 - p_N \end{bmatrix} \quad (10)$$

井筒内流体流动存在摩阻,考虑重力、粘滞摩阻和

加速度摩阻的影响,目前许多学者开展了井筒压降模型的研究^[17-19]。本文采用 Ouyang 单相模型计算由重力、摩擦、加速度3部分构成的压降,并通过摩擦系数经验修正公式融入了射孔粗糙度造成的压降。压降方程表达式为:

$$\begin{aligned}
p_j - p_{j+1} &= \rho g \frac{L_j \sin \theta_j + L_{j+1} \sin \theta_{j+1}}{2} + \frac{4 f_j \rho Q_j^2 (L_j + L_{j+1})}{\pi^2 D^5} + \\
&\quad \frac{32 \rho Q_{j+1} q_j}{\pi^2 D^4} + \frac{16 \rho q_j^2}{\pi^2 D^4} \\
&\quad (j = 1, 2, \cdots, N-1) \quad (11)
\end{aligned}$$

式中: ρ 为流体密度, kg/m^3 ; g 为重力加速度, $9.8 \text{ m}/\text{s}^2$; D 为井筒直径, m ; θ_j 为第 j 微井段与水平方向夹角, 弧度;

度; Q_j 为第 j 段处主井筒流量, $Q_j = \sum_{i=j}^N q_i, \text{m}^3$ 。

f_j 为第 j 微井段摩阻因子, 无因次, 可表示如下:

$$f_j = \begin{cases} \frac{16}{N_{\text{Re}}} (1 + 0.043 04 N_{\text{Re},w}^{0.614 2}) & \text{层流} \\ f_0 (1 - 0.015 3 N_{\text{Re},w}^{0.397 8}) & \text{湍流} \end{cases} \quad (12)$$

$$N_{\text{Re},w} = \frac{q_1 \rho}{\pi \mu}, N_{\text{Re}} = \frac{\bar{q} \rho}{D \mu}, q_1 = \frac{q_j}{L_j}, \bar{q} = Q_{j+1} + q_1 \frac{L_j}{2}$$

式中: f_0 为没有流体流入时摩阻因子, 无因次; q_1 为单位长度的流量, m^2/d ; D 为井筒直径, m ; $N_{\text{Re}}, N_{\text{Re},w}$ 分别为雷诺数和流入雷诺数, 无因次。

因此, 井筒内部每两个相邻微井段中心点之间的压降, 可以由 Ouyang 模型算得, 数学表达式为:

$$p_i - p_{i+1} = D p_i \sum_{j=1}^i q_j \quad (13)$$

代入前一方程组可得以下矩阵形式:

$$\begin{bmatrix} A_{11} & A_{12} & A_{13} & \cdots & A_{1N} \\ A_{21} & A_{22} & A_{23} & \cdots & A_{2N} \\ A_{31} & A_{32} & A_{33} & \cdots & A_{3N} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ A_{N1} & A_{N2} & A_{N3} & \cdots & A_{NN} \end{bmatrix} \begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ \vdots \\ q_N \end{bmatrix} = \begin{bmatrix} p_0 - p_1 \\ p_0 - p_1 + D p_1 q_1 \\ p_0 - p_1 + D p_1 q_1 + D p_2 (q_1 + q_2) \\ \vdots \\ p_0 - p_1 + D p_1 q_1 + \cdots + D p_{N-1} \sum_{i=1}^{N-1} q_i \end{bmatrix} \quad (14)$$

当井底流压给定, 此方程组为关于 $(q_1, q_2, \cdots, q_N)$ 的非线性方程组, 可由 Newton - Raphson 迭代法求解。

2 应用实例

安哥拉某深水油田浊积岩油藏为渗透率各向异性的非均质油藏, 油藏上、下边界封闭, 四周为边底水定压边界, 压力值为 16.55 MPa。油藏长度 1 524 m, 宽度为 610 m, 有效厚度为 61 m。复杂轨迹井在油藏内裸眼段井筒长 1 219 m, 跟端井底流压为 13.79 MPa, 沿井筒轨迹穿越油藏储层的渗透率分布如表 1 所示, 井筒粗糙度 0.000 6, 其他参数见表 1。

2.1 井筒流量及压力分布

图 3 和图 4 分别为流量和压力沿井筒的分布, 可以看出, 复杂轨迹井井筒内的流量从指端到跟端逐渐

表 1 各井段长度和渗透率

Table 1 Length and permeability of each wellbore segment

分段序号	对应段长度/m	水平渗透率/ ($10^{-3} \mu\text{m}^2$)	垂直渗透率/ ($10^{-3} \mu\text{m}^2$)
1	45.72	200	40
2	79.25	500	100
3	60.96	800	160
4	67.06	400	80
5	76.20	300	60
6	54.86	500	100
7	85.35	1 000	200
8	73.15	500	100
9	82.30	600	120
10	91.44	300	60
11	100.59	900	180
12	109.73	280	56
13	88.39	200	40
14	73.15	500	100
15	70.10	700	140
16	60.96	250	50

增大。由于储层的非均质性, 各段流量分布并不均匀, 渗透率高的部位流量也高。井筒压降从指端到跟端同样逐渐增大, 由于流量分布不均匀, 因此不同轨迹段井筒内压降在各段也不相等。结果显示跟端压力 13.79 MPa, 指端压力 14.53 MPa, 跟端压降为 2.76 MPa, 指端压降为 2.02 MPa, 井筒内压降为 0.74 MPa。井筒内压降约为跟端压差的 1/4, 指段压差的 2/5, 因此, 长井段复杂轨迹井筒内压降不可忽略, 如果忽略可导致井的产量估计过高。

对于长井段复杂轨迹井, 考虑渗透率差异性, 分段赋值计算从油藏流入井筒的流量, 并沿程计算井筒摩阻压降对产量的影响是必要的。该计算方法能够更准确地计算复杂轨迹井的产量, 更好地考虑工程和地质的需要。

2.2 与 Eclipse 结果对比

采用相同油藏、流体和复杂轨迹井参数, 对比了该方法计算结果和 Eclipse 软件计算结果, 由图 5 可知, 各节点的流量与渗透率值呈现正相关性, 计算结果与 Eclipse 模拟结果基本一致, 井筒中间段较好吻合, 两端吻合稍差, Eclipse 结果偏低, 这是因为 Eclipse 设定的边界条件难以满足定压边界, 更接近于封闭边界。

点源函数法的优势在于避免了数值模拟中数值弥散的发生, 只需输入较少的参数就可以对复杂轨迹井进行快速产能评价。而油藏数值模拟方法的数值发散现象, 以及需要输入较为准确的油藏参数, 限制了该方法在油藏评价阶段的应用。

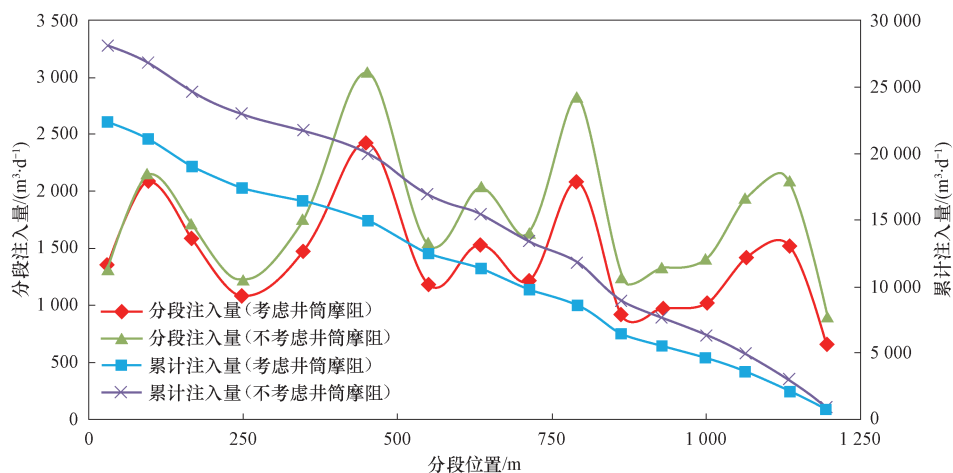


图3 分段流入量及累计流入量分布

Fig. 3 Inflow rate of different segments and cumulative pipe flow rate

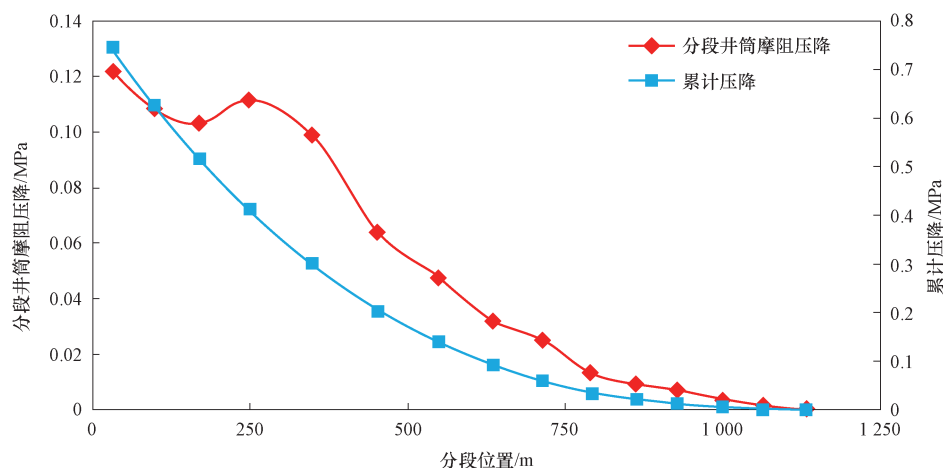


图4 分段井筒摩阻压降及累计压降分布

Fig. 4 Pipe flow pressure drop of different segments and cumulative pressure drop

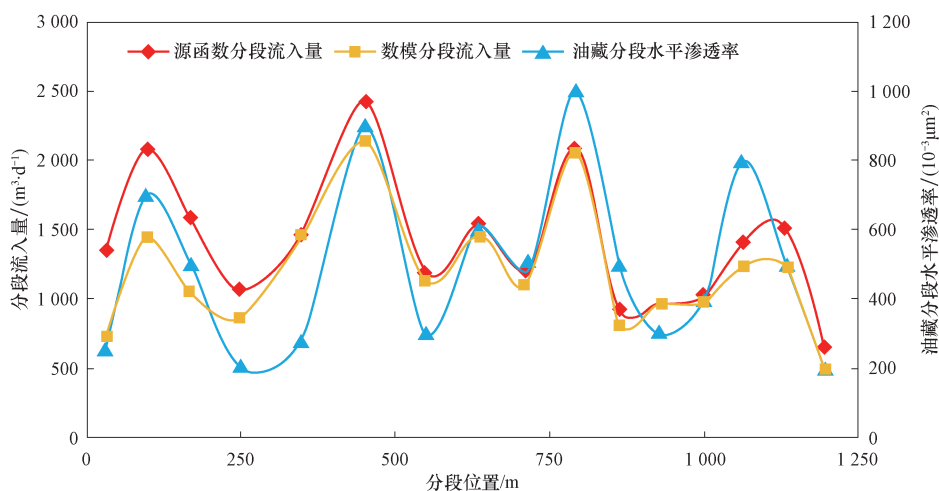


图5 点源函数与数模方法结果对比

Fig. 5 Results comparison between point source function method and Eclipse simulation

2.3 计算结果与油田现场对比

应用该方法计算了安哥拉某深水油田 A1 井在不同井底流压下的产量(图 6),井底流压越小,生产压差越

大,单井日产量也就越高。通过与油田现场测量的产量数据进行对比可以看出,预测的油井产量稍低于实际产量,这主要是模型做了简化造成的,但总体相对误差小于 5%,能满足现场油藏工程研究的需要。

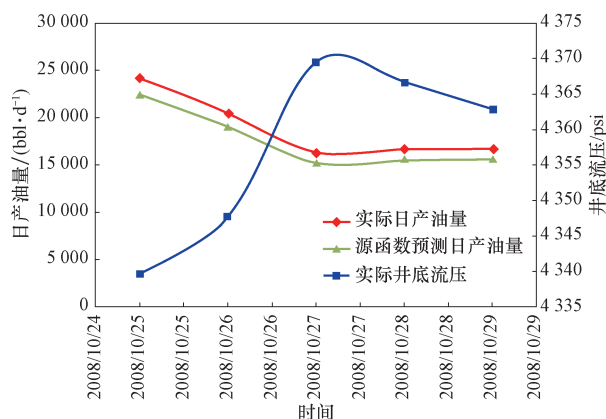


图6 新方法计算产量与现场产量对比

Fig. 6 Comparison of the calculated well production rate with the metered oil production in oilfield

3 结论与认识

应用点源函数方法计算复杂轨迹井产量,不仅考虑了油藏储层的非均质性和沿程井筒的压降损失,而且适用条件和应用范围更广,克服了传统水平井产量计算方法的不足。通过计算实例表明,该方法能准确地计算复杂轨迹井的产量,在油藏评价阶段能发挥快速便捷的作用。通过与油藏数值模拟结果对比,表明该方法是切实可行的。

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